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Bamboo based family forests offer opportunities for biomass production and carbon farming in North East India

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ABSTRACT

Although neglected in scientific research and development, bamboo based family forests (BBFF) have traditionally been managed on family farms because of their great socioeconomic value in India and other parts of Asia. Recently, there has been increasing interest in their role in biomass production and climate change mitigation. However, our knowledge of the contribution of BBFF at village and landscape level to biomass production and terrestrial carbon is very limited. Therefore, the objectives of this paper are to (1) quantify occurrence of bamboo resources in BBFF,(2) develop appropriate models for estimation of biomass of thick walled bamboos, and (3) estimate biomass and carbon stock in BBFFs in North East India. Occurrence of bamboo resources in BBFF was quantified through survey of 2850 households selected from 95 villages of Barak valley, North East India. Allometric models for biomass estimation were developed through destructive harvesting of 268 bamboo culms from *Bambusa cacharensis*, *B. vulgaris* and *B. balcooa*. The height-diameter relationships and allometric scaling between above-ground biomass (AGB), culm height (H) and diameter at breast height (D) were examined using various models.Culm height, D and AGB were allometrically related in all the three species, but the exponents were significantly larger than those expected under a geometric and stress similarity growth models. The above-ground biomass carbon density in BBFF was estimated at 16.38 Mg ha^{-1} for *B. cacharensis*, 38.42 Mg ha^{-1} for *B. vulgaris* and 19.64 Mg ha^{-1} for *B. balcooa*. In addition to the various ecosystem services provided by village grown bamboo, total biomass (52.8 Mg ha^{-1}) and carbon (25.8 Mg ha^{-1}) storage in BBFFs can offer an opportunity for carbon farming.

1. Introduction

Many bamboo species are important in local economies; their most important economic uses include food, handcraft, fencing, and cottage industry (Ahmad and Kamke, 2003). As such bamboos are a major commodity in domestic trade and subsistence use, generating over US$ 4.6 billion per year globally (Bystriakova et al., 2004). In addition, they contribute to soil and water management, and biodiversity conservation (Sheil et al., 2012). More importantly bamboo plays a crucial role as a carbon sink, thus contributing to climate change mitigation (Nath et al., 2015; Singnar et al., 2017; Yuen et al., 2017).

In India and other parts of Asia, two types of bamboo production practices can be recognized, namely "village bamboos" and "forest bamboos" (Banik, 2000; Nath et al., 2015; Singnar et al., 2017). Village bamboos are mostly thick-walled, tall species, and these are managed either in a pure stand or mixed with other tree species (Nath and Das, 2008) forming bamboo based family forests (BBFFs). Forest bamboos are mostly thin walled and grow in patches. Village bamboos have traditionally been managed with a view to increasing the socioeconomic value of the system. Bamboos are used by the rural populace for fencing, construction, roofing and crafts (Nath et al., 2009). The young shoots of some species (e.g. *Bambusa balcooa*) are edible, and shoots are harvested from first week of June to first week of September every year for consumption (Bhatt et al., 2003). There is also an increasing interest in the value of these family forests in climate change mitigation and biodiversity conservation (Nath et al., 2015; Yuen et al., 2017). Management of BBFF offers land owners an opportunity to obtain secondary source of income and environmental co-benefits (Nath et al., 2015). Most of the studies on biomass carbon storage in bamboos have concentrated on forest bamboos (Yen et al., 2010; Yen and Lee, 2011; Yen and Wang et al., 2013; Zhang et al., 2014; Singnar et al., 2017; Yuen et al., 2017) while village grown bamboo species remain little studied (Nath et al., 2009).

The high annual carbon accumulation rates (2–14 Mg ha^{-1} yr^{-1})

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suggest the potential for successful carbon farming using bamboo (Nath et al., 2015; Yuen et al., 2017; Sileshi and Nath, 2017). The clean development mechanism (CDM) promotes carbon forestry activities in the developing world as a means for mitigating climate change impacts (UNFCCC, 2002). However, CDM projects have mainly focussed on the establishment of tree planting in degraded forestland with fast growing species. Although bamboos are characterized by fast growth and high biomass productivity (Scurlock et al., 2000; Nath et al., 2015) they have been neglected in selecting fast growing species for plantation (Sohel et al., 2015). In comparison to the 10–50 years for most timber species, the harvest time for bamboos is 3–5 years (Desalegn and Tadesse, 2014). As a result bamboos possess high potential for biomass production and carbon sequestration (Wang et al., 2013; Zhang et al., 2014; Zhou et al., 2011; Nath et al., 2009; 2015; Yuen et al., 2016; 2017). Initially, bamboos were not considered in CDM projects due to the ambiguity relating to the classification of bamboos as trees under afforestation and reforestation projects (Lobovikov et al., 2012). In its 39th meeting the CDM executive board has decided that bamboos can be considered equivalent to trees for CDM afforestation and reforestation projects (Lobovikov et al., 2012) but the decision has been left to the designated national authorities to include bamboos in CDM projects (Sohel et al., 2015). As a result little progress has been made in the development of biomass estimation models and tools for bamboo-based systems. A recent synthesis has strongly recommended development of equations for predicting carbon biomass for more bamboo species (Yuen et al., 2017) and especially for village grown species for their diverse role in rural life and numerous other ecosystem services (Nath et al., 2015).

In India thick walled bamboos are mainly composed of *Bambusa* species. *Bambusa* is a large genus of clumping bamboos and most species are tall and thick (Banik, 2000). This species is widely grown in homegardens in India and Bangladesh (Banik, 2000) forming family forest. In India, the genus *Bambusa* are represented by 37 species (representing 26% of the bamboo species), and are predominantly arborescent bamboos growing in diverse regions and habitats (Sharma and Nirmala, 2015). Our knowledge of the contribution of BBFF at village and landscape level to biomass production and terrestrial carbon is very limited (Nath et al., 2015). Therefore, it is important to develop appropriate biomass estimation models for different species being managed under family forest. In this paper, our main objectives are to: (1) quantify occurrence of bamboo resources in BBFF,(2) develop appropriate models for estimation of bamboo biomass and (3) estimate biomass and carbon stock of BBFFs in North East India.

2. Materials and methods

2.1. Study area

The present study was conducted in the Barak valley (24°08′–25°08′ N and 92°15′–93°15′E) in Assam, North East India. The study area falls within the range of the Himalayan foothills and the Barak River Basin. The Barak valley, in conjunction with Cachar, Hailakandi, and Karimganj administrative districts, covers an area of ~7000 km^2 (NEDFCL, 2016). The study area is characterized by tropical humid climate. Administrative units of the study area and the number of blocks and villages in the three districts are presented in Table 1. The region has a mean annual precipitation of 3500 mm, temperature range of 13–37 °C, and relative humidity of 93.5% (NEDFCL, 2016). The dominant soil of the region is classified as the Barak series, which is fine, mixed, hyperthermic family of Aeric Endoaquepts(USDA, 1998).

In traditional homegardens of North East India, the land holding is deliberately demarcated into more micro zones or management zones based on the specific needs of the farmer. For example, Das and Das (2005) recognized five major management zones in homegardens based on their function, location and composition: (i) bamboo groves (ii) betel groves (iii) banana groves (iv) vegetable garden, and (v) dense or extended zones. In bamboo groves, bamboo is grown either in pure stands or mixed with dicotyledonous tree species such as *Lagerstroemia*, *Bombax* and *Erythrina* (Nath and Das, 2008) forming a small scale forest. Inventory of village bamboo species in BBFF revealed the dominance of the genus *Bambusa*. Based on their high frequency of occurrence, *B. cacharensis*, *B. vulgaris* and *B. balcooa* have been designated as the priority species in the study area (Das and Das, 2005; Nath and Das, 2008). These three species represents 90% of the total growing stock of BBFF (Nath and Das, 2008). Therefore, this study focussed on evaluating these priority species to represent biomass and carbon storage in BBFF as a whole.

Table 1
Administrative units of Barak valley, North East India and number of villages surveyed for the present study.

District	Cachar	Hailakandi	Karimganj
Block*	15	5	7
Villages*	1047	331	940
Household per village*	297	402	239
Number of villages surveyed	50	15	30
Number of household surveyed	1500	450	900
Average size of BFF (ha)†	0.08 (0.02–0.67)	0.05 (0.01–0.23)	0.04 (0.02–0.42)

Figures in parenthesis are range of mean value from minimum to maximum.
* Source: Statistical Hand Book Assam, Directorate of Economics &Statistics, Govt, of Assam, 2011, BFF: Bamboo Based Family Forest.
† Mean values were calculated over households.

2.2. Selection of villages and representative culm and clump

The selection criteria for villages were to cover 5% of the total villages from each district. Representative villages were selected by surveying at least three or more villages randomly from all the blocks in each district. Therefore, a total of 50, 15 and 30 villages from Cachar, Hailakandi and Karimganj district respectively were selected for the present study (Table 1). Occurrence of bamboo clumps in each village was studied by randomly selecting 30 household from each village. Therefore, a total of 1500, 450 and 900 households from Cachar, Hailakandi and Karimganj district respectively were surveyed. During the field visits, the size (ha) of BBFFs and total number of clumps of *B.cacharensis*, *B.vulgaris* and *B. balcooa* in each household were enumerated. In total 2850 households from three districts were surveyed to estimate the size of BBFFs and clump level information. During household survey, the number of culms of different aged stands viz. 1-yr, 2-yr, 3-yr, 4-yr in each clump of the selected households were counted. The average number of clumps per BBFF in each district and the number of culms per clump in bamboo stands of different ages are presented in

Table 2
Number of bamboo clumps per bamboo family forests (BFFs) in each district and number of culms per clump in North East India.

	District/Age	*B. cacharensis*	*B. vulgaris*	*B. balcooa*
Average number of Clumps in BFFs	Cachar	4.5 (1–37)	2.5 (1–7)	1.2 (1–5)
	Hailakandi	1.8 (1–5)	3.7 (1–18)	1.1 (1–5)
	Karimganj	2.4 (1–15)	1.8 (1–12)	1.2 (1–17)
Number of culms/ clump in different ages	1-yr	28 (12–45)	32 (12–49)	16 (08–27)
	2-yr	34 (16–50)	24 (14–43)	34 (10–48)
	3-yr	17 (9–35)	15 (11–35)	18 (07–32)
	4-yr	18 (10–29)	19 (08–30)	27 (09–38)
Total number of culms/clump		97 (75–127)	90 (65–125)	95 (72–118)

Values are mean; Figures in parenthesis are range of mean value from minimum to maximum.

Table 2.

2.3. Biomass data collection

Primary field data for biomass model development were collected from a bamboo grove in Cachar district in Assam (longitude 92°45″East and latitude 24°41″North). We chose Cachar district due to its proximity to our institution (Assam University) and the bamboo stands are relatively representative of Barak Valley (Nath and Das, 2008). There exists considerable environmental heterogeneity in Assam, and this poses challenges to collect a representative sample. Being a valley region, of Southern Assam weather of the study area has been almost stable over the three districts. In this study, a more intensive sampling was undertaken focussing on Cachar district. Although a sample size of about 50 individual stems is considered adequate for developing allometric models (e.g. Sileshi, 2014), a sample size of 80–108 culms was taken in order to make the models robust enough.

A destructive sampling method was employed for the estimation of biomass following approximate age classes established as follows: (i) 1-yr old culms are those that emerged in the current year and have only a few leaves, sheaths attached to culm, and pale green culm surface covered with clear white powder; (ii) 2-yr old culms (actual age may be 1–2 yr) have few sheaths at the base of culms, have dark green colour and well developed branches on 5th and 6th internodes; (iii) 3-yr old culms (actual age may be 2–3 yr) have no sheath, have mature green colour and lichens and mosses start to appear on culm surface; and (iv) 4-yr old culms (actual age may be 3–4 yr), sheath is absent, culm colour is light yellowish green with abundance of lichens and mosses. The culm circumference at breast height (CBH) was measured at 1.3 m from ground. The culm diameter used to develop the various allometric equations ranged between 2.2 cm and 12.5 cm.

Depending on the culm sizes, 9 (nine) different girth classes were recognized for *B. cacharensis* and 10 girth classes for *B. vulgaris* and *B. balcooa* representing the whole diameter range. From each girth class 3 culms of *B. cacharensis* were harvested and 2 of *B. vulgaris* and *B. balcooa* were harvested from each of the four age classes. In total 27 culms were harvested per age classes of *B. cacharensis* and 20 culms per age classes of *B. vulgaris* and *B. balcooa*. Thus a total of 268 culms were harvested for the present study. After harvesting, culm samples were divided into leaf, branch and culm components and their respective fresh weights were recorded in the field. A sub-sample of each component was oven dried at 70 °C to a constant weight in order to calculate the dry matter of each component. Culm, branch and leaf biomass were determined from their respective dry weight to fresh weight ratio. Summing all the biomass components yielded the above ground standing biomass. Total stand biomass for the different culm age classes for the three species were determined and then computed on a hectare basis. Carbon stock of the bamboo stand was calculated by considering 47% of the biomass as carbon content (Nath et al., 2009).

3. Statistical analyses

3.1. Comparing height-diameter models

Many growth and biomass-projection systems use height (H) and diameter (D) as the two basic input variables. However, H is relatively more difficult and time consuming to obtain than D (Huang et al., 2000). Therefore, H-D models are often used to predict the missing heights from field measurement of diameters. We compared 12 of the most commonly used H-D models in bamboos (Kaushal et al., 2016; Singnar et al., 2017) to identify the best model for predicting H-D relationship and estimating the maximum height (H_{max}) in *Bambusa* species. These functions are given below.

Asymptotic: $H = a - bc^{D}$

Chapman–Richards: $H = a(1 - exp(-bD))^{c}$

Exponential (2 parameter): $H = a(exp(bD))$

Exponential (3–parameter): $H = a - b(exp(-cD))$

Gompertz: $H = a(-exp(b - cD))$

Hyperbolic models: $H = a + \frac{b}{D}$

Logistic: $H = \frac{a}{(1 + \exp(b - cD))}$

Michaelis–Menten: $H = \frac{aD}{b + D}$

Monomolecular: $H = a(1 - exp(-b(D - c)))$

Power law: $H = aD^{b}$

Richards function: $H = \frac{a}{(1 + \exp(b - cD))^{1/d}}$

Weibull: $H = a - b(exp(-cD^{d}))$

Except the power law in all of the functions, a is the asymptotic height (H_{max}), which is often used as a measure of tree species size (Thomas, 1996).In order to maintain adequate sample size and increase the power of test, the H-D models were tested after combining the datasets for the three species. All models were fitted using the nonlinear procedure (PROC NLIN) with the Marquardt algorithm in the SAS system. The Marquardt algorithm was preferred because it is a Gauss-Newton algorithm with a ridging penalty, which makes it more robust than other algorithms.

3.2. Estimating allometry parameters

In order to test the hypothesis that biomass accumulation in thick walled bamboos follows allometric scaling rules, the data were fitted to a simple power-law function given as:

$$H = \alpha D^{\beta} + \varepsilon \quad (1)$$

Where H is total height, D is diameter at breast height, α is the normalization (proportionality) constant, β is the exponent and ε is the error term. Model 1 is usually fit to data with the assumption of homoscedastic errors. In order to overcome non-normality of errors and for ease of analysis the linear form of the above function is often used. This involves logarithmic transformation of both the Y and X variables. For comparison with model 1 we also transformed the data taking the natural logarithms as follows:

$$ln(H) = ln(\alpha) + \beta(lnD) + e \quad (2)$$

where ln(α) is the intercept, β is the slope and e is the error term. In order to account for the back-transformation of the error in Model 2, H was calculated as $H = \alpha D^{\beta} \times CF$ where CF is the correction factor. The CF was calculated from the mean square of error (MSE) as $exp(MSE/2)$ because this is a requisite step in back-transformation of data in allometry (Sileshi, 2014; Yuen et al., 2016). Comparison of the residuals from Models (1) and (2) revealed less normality of errors in Model (2). Therefore, allometry parameters and predictions were generated using Model (1).

There are different theoretical models derived from physical and biological first principles that predict universal scaling between $H$and D (Price et al., 2007). These are the geometric similarity, stress similarity, elastic similarity and metabolic theory of ecology (MTE) (Niklas, 1995; West et al., 2009). The geometric similarity model assumes scaling of H with D as αD^{1}. The constant stress similarity model, also called the concept of adaptive growth and uniform stress theory suggests that the shape of a tree's stem is influenced by mechanical loading. It assumes that the trunk tapers such that stress produced by wind pressure along

the stem is equalized resulting in total height (H) scaling with diameter (D) as $H = \alpha D^{1/2}$. According to the elastic similarity model a tree trunk is a self-supporting tapering column and thus H will scale with D as $\alpha D^{2/3}$ to resist buckling of the tree under its own weight. The MTE uses scaling relations based on metabolism and biomechanics to quantify how trees use resources, fill space, and grow (Enquist et al., 1999; West et al., 2009). Nevertheless, its scaling exponent is the same as that of the elastic similarity model, i.e. $H = \alpha D^{2/3}$. According to MTE, AGB scales with H and D as αH^4 and $\alpha D^{8/3}$, respectively (West et al., 2009). In the present analysis we determined the empirical exponents for the different age-classes as well as the combined data. Then we compared the empirical values with the theoretical predictions. Empirical and theoretical values were declared significantly different from each other only when the 95% confidence limits of the empirical estimates do not encompass theoretical values.

3.3. Estimating biomass and carbon stocks

Biomass estimation models based on diameter at breast height (D at 1.3 m) alone or including total height (H) or/and wood density (ρ) have been widely used in predicting tree biomass (Sileshi, 2014). In this study, we first tested three types of species-specific models. The first one is a simple power-law (allometric) model that includes only D as in Model (2). The only difference is that here H is replaced by AGB, and hereafter it will be referred to as Model (2) for biomass. The second model consists of only H given as Model (3) below, while the third model consists of both H and D as in Model (4) below:

$$ln(AGB) = ln(\alpha) + \beta(lnH) + e \quad (3)$$

$$ln(AGB) = ln(\alpha) + \beta(\ln(HD^2)) + e \quad (4)$$

where HD^2 represents culm volume and ln(α),β and e were defined as in Model (1). In each model fitted lines were generated by multiplying predicted values with the correction factor.

The suitability of each model was compared based on the AIC weights, pseudo R^2 and MSE. AIC weights are more informative than AIC values when comparing biomass estimation models (Sileshi, 2014). The AICw was calculated following the method described in Johnson and Omland (2004). AICw indicates the probability that the model is the best among the whole set of candidate models. Therefore, it provides a measure of the strength of evidence for each model (Johnson and Omland, 2004).

3.4. Estimating C accumulation rates

Converting potential carbon stocks into C accumulation rates requires knowledge of the time needed to reach the potential. Long-term observations of C stock increments over several decades are not available for the species studied here. Based on the age of the clumps, which was 15 years for *B. cacharensis*, 17 years for *B. vulgaris* and 12 years for *B. balcooa,* we assumed the clump age as reasonable time to reach maximum carbon stocks. Then we estimated the C accumulation rates (Mg ha^{-1} yr^{-1}) by dividing the potential C sequestration by the accumulation time for each species.

4. Results

4.1. Occurrence of BBFFs and bamboo clump

The size of BBFF ranged between 0.01–0.67 ha with a mean value of 0.05 ha (Table 1). Across districts and species, the number of clumps per BBFF ranged between 1 and 37 with a mean of 6.7 clumps per BBFF (Table 4). *B. cacharensis* dominated the total growing stock (43%) followed by *B. vulgaris* (40%) and *B. balcooa* (17%). The total number of culms per clump ranges between 90 in *B. vulgaris* to 97 in *B. cacharensis* (Table 2). In *B. cacharensis* and *B. vulgaris*, over 60% of the total culms per clump was represented by 1–2 year old individuals (Table 2).

Table 3
Estimates of the maximum height (Hmax) and comparison of height-diameter (H-D) models using the AICw, pseudo R^2,root mean square of error (RMSE), and *P* value of the Shapiro-Wilk test of normality of errors.

Model	Hmax	AICc	AICw	R^2	RMSE	Shapiro-Wilk
Power law	NA	**2327.2**	**0.39**	**0.922**	**76.2**	0.3421
Chapman-Richard	3969.0	2328.1	0.25	0.922	76.2	0.3446
Weibull*	6467.7*	2329.7	0.11	0.922	76.3	0.3887
Asymptotic	2755.3	2329.9	0.10	0.922	76.5	0.2898
Monomolecular	2753.7	2329.9	0.10	0.922	76.5	0.2898
Michaelis-Menten	3310.4	2333.0	0.02	0.920	77.1	0.6192
Gompertz	2184.1	2334.4	0.01	0.920	77.1	0.1618
Richard*	2175.6*	2336.6	0.00	0.920	77.3	0.1593
Logistic	1986.1	2339.1	0.00	0.919	77.8	0.0989
Exponential (3-p)*	−17659.0*	2360.7	0.00	0.912	81.0	0.2363
Exponential (2-p)	674.1	2430.0	0.00	0.885	81.0	0.0003
Hyperbolic	1877.5	2533.2	0.00	0.831	112.0	0.0078

Letter in bold face refers to best model.
* Model did not converge. Therefore, the estimates of Hmax were deemed unreliable.

4.2. The H-D model

Among the H-D models compared, the power-law function had 40% likelihood of being the best followed by the Chapman-Richard model (26% likelihood), while the rest of the models had < 12% likelihood (Table 3,). The changes in terms of the explained variation (pseudo R^2) among the models were marginal (Table 3). Some models especially the 3-parameter exponential, Richard and Weibull functions failed to converge, and these were deemed unsuitable for the data. Therefore, the estimates of H_{max} from those models that failed to converge were deemed unreliable. Among the asymptotic models, H_{max} estimated using the Chapman-Richard model was deemed the best based on the Akaike weights (Table 3). However, for prediction of H, the power law model was deemed the best, and its parameters are presented in Table 3.

4.3. Allometric scaling

Culm height, D and AGB were allometrically related in all the three species (Table 4 and 5; Fig. 1 and 3). The exponents of the H-D scaling in *B. cacharensis* and *B. balcooa* were not significantly different from the value of 0.67 predicted by metabolic theory of ecology (Table 4). On the other hand, in *B. vulgaris* the exponent was significantly lower than 0.67. In all cases, the exponents were significantly smaller than those expected under the geometric and stress similarity growth models.

Table 4
Parameter estimates of the height-diameter (H-D) allometry and goodness of fit statistics for three species and combined.

Species	Sample size	Intercept (α)	Slope (β)	R^2	Shapiro-Wilk*
B. cacharensis	108	431.1 (395.7; 466.4)	0.57 (0.53; 0.62)	0.862	0.066
B. vulgaris	80	452.6 (411.0; 494.1)	0.58 (0.52; 0.63)	0.904	0.005
B. balcooa	80	387.3 (354.5; 420.1)	0.64 (0.59; 0.68)	0.930	0.012
Combined	268	407.4 (388.7; 426.1)	0.62 (0.59; 0.64)	0.912	0.3421

Figures in parenthesis represent 95% confidence limits. The slopes of two or more species were deemed significantly different when their 95% confidence limits do not overlap.
* P value of the Shapiro-Wilk test of normality of the residuals.

Table 5
Parameter estimates of the various biomass models and goodness of fit statistics for three species and combined. The P values of Shapiro-Wilk test of normality of residuals are given in the last column.

Species	Model	Intercept (lnα)	Slope (β)	R^2	RMSE	AIC	AICw	Shapiro-Wilk
B. cacharensis	2	−1.9 (−2.1; −1.6)	2.18 (2.04; 2.31)	0.904	0.251	**−294.7**	**0.99**	**0.188**
(N = 108)	3	−19.6 (−21.7; −17.4)	3.03 (2.72; 3.34)	0.773	0.385	−201.7	0.00	0.221
	4	−6.8 (−7.3; −6.2)	0.82 (0.76; 0.88)	0.895	0.262	−285.1	0.01	0.226
B. vulgaris	2	−1.3 (−1.6; −1.0)	2.04 (1.86; 2.21)	0.878	0.201	**−252.3**	**0.68**	**0.063**
(N = 80)	3	−19.9 (−22.5; −17.2)	3.12 (2.75; 3.49)	0.783	0.269	−206.2	0.00	0.733
	4	−6.1 (−6.8; −5.4)	0.79 (0.73; 0.85)	0.876	0.203	−250.8	0.32	0.418
B. balcooa	2	−1.7 (−2.1; −1.4)	2.31 (2.13; 2.49)	0.892	0.208	−247.0	0.00	0.029
(N = 80)	3	−21.6 (−23.4; −19.8)	3.39 (3.14; 3.64)	0.900	0.2	−253.2	0.03	0.644
	4	−6.9 (−7.6; −6.2)	0.87 (0.81; 0.93)	0.908	0.193	**−259.9**	**0.96**	**0.181**
Combined	2	−2.1 (−2.2; −1.9)	2.41 (2.31; 2.51)	0.915	0.262	−713.9	0.24	0.008
(N = 268)	3	−22.7 (−24.0; −21.5)	3.51 (3.32; 3.70)	0.854	0.343	−569.9	0.00	0.009
	4	−7.5 (−7.9; −7.2)	0.91 (0.87; 0.95)	0.916	0.261	**−716.2**	**0.76**	**0.032**

Figures in parenthesis are 95% confidence intervals. RMSE = Department of Biotechnology.
Model 2 is ln(AGB) = ln(D); Model 3 is ln(AGB) = ln(H); Model 4 is ln(AGB) = ln(HD^2).
Letter in bold face refers to best model.

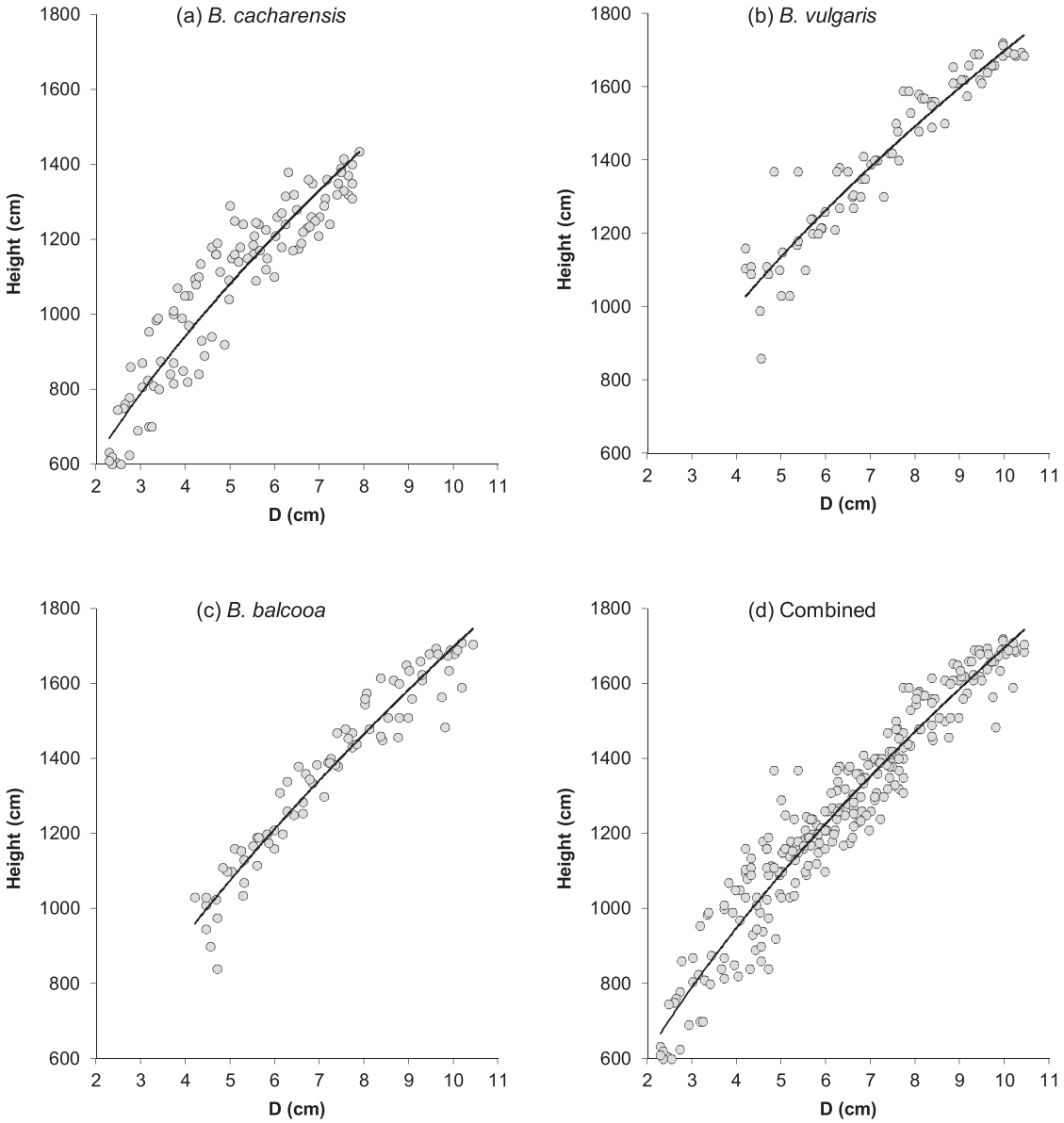

Fig. 1. Allometric scaling between culm height and diameter at breast height (H-D scaling). Solid black lines are fitted lines representing back-transformed values of predictions multiplied by the correction factor.

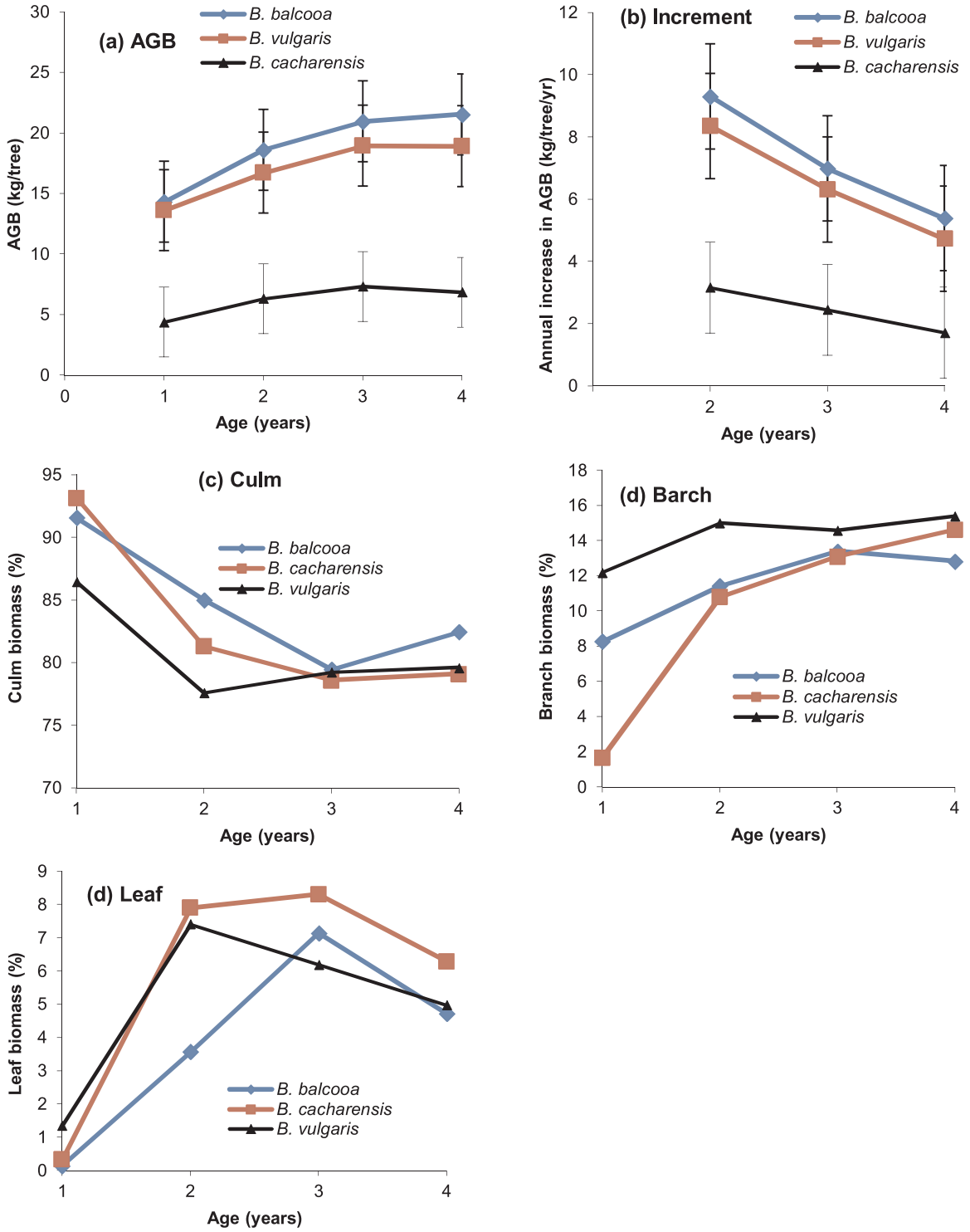

Fig. 2. Variation in AGB (a), annual increment rate in AGB (b) and the percentage contribution of culm (c), branch (d) and leaf (e) with species and culm age. Error bars in a and b represent the 95% confidence limits.

The scaling of AGB with H was consistent with the geometric similarity model (slope of 3) in all three species (Table 5). None of the species conformed to the predictions of MTE. With overlapping 95% confidence intervals, the intercepts and slopes of the H-D allometry also did not significantly differ among species (Table 5). Therefore, the data for the three species were combined for further analysis. The parameters estimated point to the fact that a single H-D model is adequate for the three species (Table 5, Fig. 1d). According to the AICw, Model 2 had a 99% and 68% likelihood of being a better model for estimating AGB of *B. cacharensis* and *B. vulgaris*, respectively. On the other hand, Model 4 had 96% and 76% likelihood of being a better model for *B. balcooa* and all species combined, respectively (Table 5).

4.4. Variation in D, H and AGB with species and age

Culm D, height and AGB significantly varied ($P < 0.0001$) with species. Only AGB significantly ($P = 0.0022$) varied with culm age, while D and H did not significantly vary with culm age. The interaction

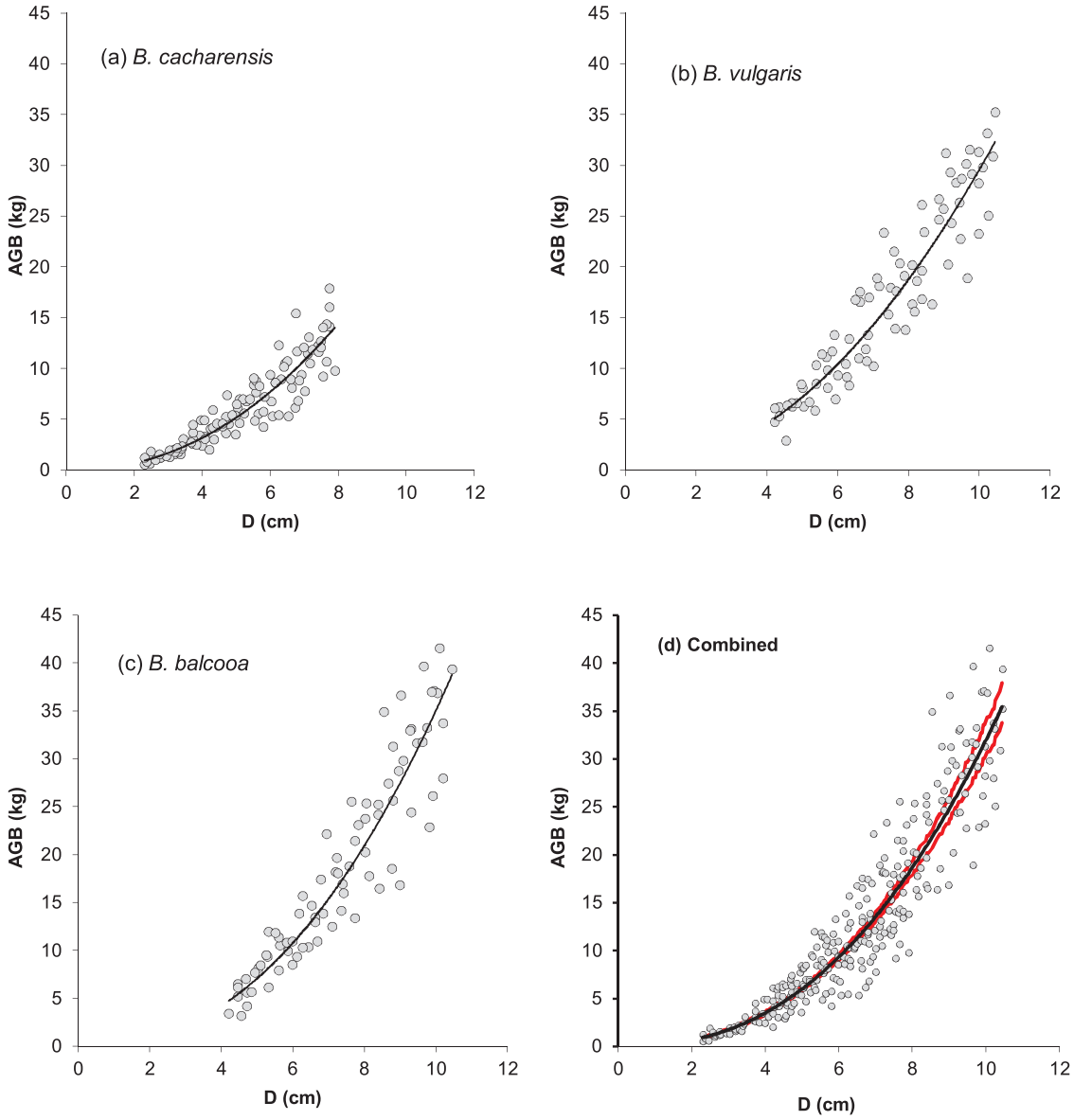

Fig. 3. Allometric relationship between above ground biomass (AGB) and diameter at breast height (D) of three different bamboo species (a–b), and the combined data (d).The red lines in Fig. 1d represent the upper and lower 95% confidence limits of the predictions. Solid black lines are fitted lines representing back-transformed values of predictions multiplied by the correction factor (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 6
Measured above-ground biomass (kg culm^{-1}) for priority bamboos of Barak Valley.

Culm age (years)	*B. cacharensis*	*B. vulgaris*	*B. balcooa*
1	4.4 b	13.6 a	14.3 a
2	6.3 ab	16.7 a	18.6 a
3	7.3 a	18.9 a	21.0 a
4	6.8 ab	18.9 a	21.5 a
Mean	6.2	17.0	18.8

Letters a and b represent post-hoc comparison of means. Figures followed by the same letters in a column are not significantly different from each other according to Tukey's HSD test.

effect of species and age on D, height and AGB was also not statistically significant. The variation in AGB with culm ages are presented in Fig. 2. *B. balcooa* and *B. vulgaris* accumulated biomass faster than *B. cacharensis*. The changes in AGB with age also followed the same pattern in *B. balcooa* and *B. vulgaris*, which was different from patterns observed in *B. cacharensis* (Fig. 2). The mean annual increment rate of AGB also significantly varied with species, culm age and their interaction effects (Fig. 2b). The increment in AGB was highest in the second year and then decreased gradually. The largest contribution to AGB (77–93%) came from the culm biomass (Fig. 2c), followed by 2–15% from branch biomass (Fig. 2d) and leaf biomass (Fig. 2d). However, these contributions significantly varied ($P < 0.0001$) with species and culm age. The contribution of branch biomass to AGB was higher in *B. vulgaris* than *B. balcooa* and *B. cacharensis*.

4.5. Biomass and carbon stocks

Measured aboveground biomass (AGB) (kg culm^{-1}) varied with the age of the culm (Table 6). In *B. cacharensis*, AGB increased with increase in culm age up to 3-yr and declined thereafter in 4-yr. In contrast, in *B. vulgaris* and *B. balcooa* AGB increased with culm age, but the increases were not statistically significant. At any given age, *B. balcooa* and *B.*

Table 7
Measured above-ground biomass and carbon density of bamboo based family forests in North East India.

Bamboo based family forest	Culm density (number ha^{-1})	Biomass storage ($Mg\ ha^{-1}$)	Carbon density ($Mg\ ha^{-1}$)	Mean annual carbon accumulation rate ($Mg\ ha^{-1}\ yr^{-1}$)*
B. cacharensis	5626	34.88	16.39	1.3
B. vulgaris	4800	81.74	38.42	2.3
B. balcooa	2216	41.79	19.64	1.6

* The C accumulation time was 15, 17, 12 years for *B. cacharensis*, *B. vulgaris* and *B. balcooa*, respectively.

vulgaris accumulated significantly higher AGB than *B. cacharensis*.

Table 7 presents the measured AGB and carbon density for each species. The average culm density in BBFF was estimated at 5626, 4800 and 2216 culms ha^{-1} for *B. cacharensis*, *B. vulgaris* and *B. balcooa*, respectively. The AGB estimated at 34.9 $Mg\ ha^{-1}$ for *B. cacharensis*, 81.7 $Mg\ ha^{-1}$ for *B. vulgaris* and 41.8 $Mg\ ha^{-1}$ for *B. balcooa*. Accordingly, the carbon density in BBFF was estimated at 16.4 $Mg\ ha^{-1}$ for *B. cacharensis*, 38.4 $Mg\ ha^{-1}$ for *B. vulgaris* and 19.6 $Mg\ ha^{-1}$ for *B. balcooa* (Table 7). The estimated C accumulation rate was 1.3, 2.3 and 1.6 $Mg\ ha^{-1}\ yr^{-1}$, corresponding to 4.7, 8.3 and 6.0 $Mg\ ha^{-1}\ yr^{-1}$ of sequestered CO_2 equivalent in *B. cacharensis*, *B. vulgaris* and *B. balcooa*, respectively.

5. Discussion

The results of this study have significant implications for BBFF management. In Asia, the history of village grown bamboo is inextricably interwoven with human history so much that parts of Asia could be described as a “bamboo civilization” (Nath et al., 2016). Bamboo is particularly important for rural livelihoods (Lobovikov et al., 2012) and in North East India BBFs have been managed to fulfil diverse social, ecological and economic benefits. The existing selective harvesting of mature culms in BBFFs prevents culms from deteriorating due to age, which would release carbon stored in the culm back into the atmosphere (Yuen et al., 2017).

This study has established allometric relationships between H and D in the thick walled bamboos *B. cacharensis*, *B. vulgaris* and *B. balcooa*. Comparison of the H-D models indicated that the power-law model is the best for predicting H from D in the three *Bambusa* species studied. The gain in explanatory power from the other models was negligible. Similarly, the power-law model was found to be more appropriate for modelling the Male bamboo (*Dendrocalamus strictus*) (Kaushal et al., 2016) and thin walled bamboos in India (Singnar et al., 2017). Except in *B. vulgaris* the H-D relationships were found to be consistent with predictions of the metabolic theory of ecology (West et al., 2009). However, the exponents of the relationship between AGB and D significantly deviated from predictions of the metabolic theory of ecology. Among the models used for predicting AGB, the model including culm volume proved to be more appropriate when data for all species were combined.

Increase in culm biomass ($kg\ culm^{-1}$) with age in *B. vulgaris* and *B. balcooa* is consistent with the trend observed for other forest bamboos (*Schizostachyum dullooa* and *Melocanna baccifera*) from India (Singnar et al., 2017). Dry matter accumulation is known to increase with culm maturation (Shanmughavel et al., 2001; Yen, 2015) resulting in increases in culm biomass with age. Mean measured AGB ($kg\ culm^{-1}$) of *B. cacharensis* was 64% lower than that of *B. vulgaris* and 67% lower than that of *B. balcooa*. Comparatively low culm biomass in *B. cacharensis* is due to its smaller size (DBH) and lower plant height than*B. vulgaris* and *B. balcooa* (Nath et al., 2006).

Although *B. cacharensis* had higher culm density in BBFF, its low culm biomass ($kg\ culm^{-1}$) meant that it had lower contribution to total biomass storage. The biomass density recorded in this study was comparable with those reported for the thin walled bamboos *S.dullooa* (44.7 $Mg\ ha^{-1}$), *P. polymorphum* (43.0 $Mg\ ha^{-1}$), and *M.baccifera* (118.4 $Mg\ ha^{-1}$)(Singnar et al., 2017). Biomass storage in BBFF was also comparable with values reported for betel palm (*Areca catechu*) plantation (47 $Mg\ ha^{-1}$) and degraded forests (42 $Mg\ ha^{-1}$) of North East India (Brahma et al., 2017). Although we were unable to directly measure root biomass and soil C, using values of belowground C storage reported in the literature (Isagi et al., 1994; Tripathi and Singh, 1996; Zhou and Jiang, 2004) we estimate belowground carbon in our bamboo stands at 38.3 $Mg\ ha^{-1}$, 89.6 $Mg\ ha^{-1}$, and 45.7 $Mg\ ha^{-1}$ for *B. cacharensis*, *B. vulgaris*, and *B. balcooa* respectively. We estimated the root to shoot ratios based on the following studies. According to Tripathi and Singh (1996) carbon stock in *Dendrocalamus strictus* stands in Indian dry tropics amounting are 75.4 $Mg\ ha^{-1}$, of which 70–75% are stored in the soil. According to Zhou and Jiang (2004) total carbon storage capacity in typical Moso bamboo (*Phyllostachy pubescens*) ecosystem was 106.36 $Mg\ ha^{-1}$, of which 72.1 $Mg\ ha^{-1}$(or 67.8%) was stored in belowground pools. Similarly, the total carbon storage in *Phyllostachys bambusoides* stands in Japan was 165.1 $Mg\ ha^{-1}$, of which 68.3% is stored in the belowground pool (Isagi et al.,1994).

The biomass carbon density of BBFF falls within the range of values (16–128 $Mg\ ha^{-1}$) reported for bamboos worldwide (Sohel et al., 2015; Yuen et al., 2017). Our estimated ecosystem carbon is 54.7 $Mg\ ha^{-1}$, 128 $Mg\ ha^{-1}$, and 65.3 $Mg\ ha^{-1}$ for *B. cacharensis*, *B. vulgaris*, and *B. balcooa* respectively. In addition, bamboos can produce a stable form of soil carbon known as phytolith occluded carbon resulting from decomposing vegetation (Huang et al., 2014). Recent studies have revealed that phytolith in bamboo may contain 0.2–5.8% of phytolith occluded carbon (Parr et al., 2010). This kind of carbon is highly resistant to decomposition and may accumulate as a fraction of organic matter that remains in the soil for several thousand years.

The above-ground biomass carbon density reported in the present study is higher than forest bamboo species from similar geographical location including *S. dullooa* (22.7 $Mg\ ha^{-1}$) and *P.polymorphum* (21.3 $Mg\ ha^{-1}$) (Singnar et al., 2017). Higher carbon density in BBFF over forest bamboo species is attributed to the thick walled nature of the village grown species. Forest bamboo species are mostly thin walled (Nath et al., 2012; Singnar et al., 2017) and therefore accumulates comparatively less biomass carbon than thick wall bamboo species. Moreover, existing plantation management practices (e.g. nutrient application, harvest cycle, etc.) can influence the biomass carbon stock of bamboo stands (Yuen et al., 2017).

In addition, selective culm felling in BBFF could have accelerated bio-carbon sequestration resulting in high biomass carbon stock in bamboo stands. Selective felling of mature bamboo culm is the common managerial practice in the BBFF of North East India (Nath and Das, 2011). Such management practice results in maintenance of a steady stock of standing culms and subsequently a stable biomass carbon stock over the period. In the ‘Luong’ bamboo (*Dendrocalamus barbatus*) in the northwest uplands of Thanh Hoa province in Vietnam, Ly et al. (2012) found higher biomass carbon stocks under selective harvesting of mature bamboo culms. Similarly, Lou et al. (2010) demonstrated under regular harvest system a Moso bamboo (*Phyllostachys edulis*) plantation in subtropical southeast China can sequester approximately as much carbon as a plantation of fast-growing Chinese fir (*Cunninghamia lanceolata*).A stand population structure dominated by younger culms is the indicator of optimum yield in the sympodial bamboo species (Yuming et al., 2011). In the present study it was observed that for the three *Bambusa* sp. > 55% of the total culms in the stand were represented by 1-yr and 2-yr old culms indicating the prevalence of a sustainable management system adopted by the farmers in BBFF.

The C accumulation rates (1.3–2.3 $Mg\ ha^{-1}\ yr^{-1}$) recorded in this study and earlier reports (1–14 $Mg\ ha^{-1}\ yr^{-1}$) (Nath et al. 2015; Yuen et al. 2017) indicate that bamboos have higher or equivalent C accumulation rates as treesin aboveground biomass: 3.6–4.9 $Mg\ ha^{-1}\ y^{-1}$in

rubber tree plantations (Kongsager et al., 2013), 1.7–7 Mg ha^{-1} yr^{-1}in other plantations (Fonseca et al., 2011) and 0.2–7 Mg C Mg ha^{-1} yr^{-1}in agroforestry (Luedeling et al., 2011). This high C accumulation rates suggests the potential for successful carbon farming using bamboos. The C thus sequestered (4.7–8.3 Mg CO_2 ha^{-1} yr^{-1}) can potentially be sold as CO_2 emission offsets. The acceptance of bamboos in volunteer carbon finance mechanisms has recently amplified the attractiveness of bamboos as plantation species (Darabant et al., 2014). Through adoption of BBFFs, smallholder farmers can benefit from the emerging carbon markets such as REDD+.

One of the uncertainties in the long term carbon management through bamboo is the gregarious flowering, die back of stands(Lou et al., 2010) and concomitant loss of system carbon (Yuen et al., 2017). The three *Bambusa* sp. managed in BBFF flowers sporadically (Banik, 2000; Das et al., 2017a, b). Under the 'sporadic flowering' phenomenon only a few culms in the stand flower and die (Das et al., 2017a, b) in contrast to 'gregarious flowering' where entire populations flower simultaneously and die subsequently. For example, *Schizostachyum dullooa* flowered gregariously in Barak valley region of North East India in 2010 and all the population died subsequently (Nath and Das, 2010). Therefore, the flowering behaviour of the *Bambusa* spp. in BBFF halts the possibility of system carbon loss through gregarious flowering and ensures the storage of vegetation and soil carbon as a long term sinks. Hence management of BBFF can store high biomass carbon and its permanency in the system carbon management can offer an opportunity for consideration of village bamboo species for carbon farming.

In this study we were unable to establish below-ground and soil C storage due to resource limitations. Other C pools such as litter, dead wood and soil organic matter, were also not studied here due to resource limitations. However, based on the range of root to shoot ratios provided by Yuen et al. (2017) for *Bambusa* species, we estimated a C allocation pattern of 80% in aboveground and 20% in belowground biomass. Assuming this ratio is reasonable, at least 4–7 Mg ha^{-1} would be stored belowground within the root system of each of the *Bambusa* species. In addition, bamboos can produce phytolith occluded carbon, a stable form of carbon resulting from decomposing vegetation that remains in the soil for several thousand years (Huang et al., 2014). Therefore, the values presented here only represent a small fraction of the C sequestration potential of bamboos in family forests.

6. Conclusions

This study has established allometric relationships between H, D and AGB, and between H and D in the thick walled bamboos *B. cacharensis* and *B. balcooa*. From the analysis above it can be concluded that a single H-D power-law model is adequate for estimating the height of the three *Bambusa* species. It can also be concluded that the use of volume provides better biomass prediction than either culm diameter or height alone for thick walled bamboos. The C accumulation rates estimated for the three *Bambusa* species were comparable with values reported for other bamboo species worldwide and many other plantation species. Therefore, management of BBFFs can offer an opportunity for carbon farming and carbon trading. Bamboos also have several additional benefits including firewood, construction materials and raw materials for handicrafts. When deployed in the right condition, bamboos can also help in rehabilitation of degraded land, protection of watersheds and contribute to conservation of biodiversity. The limitation of this study is that the data come from one site, and therefore it may not adequately cover all the environmental heterogeneity. Therefore, we recommend that the biomass estimation models presented here be validated before use in other locations.

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